All set, indeed! N2pc components reveal simultaneous attentional control settings for multiple target colours

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Abstract

To study whether top-down attentional control processes can be set simultaneously for different visual features, we employed a spatial cueing procedure to measure behavioural and electrophysiological markers of task-set contingent attentional capture during search for one or two possible colour-defined targets (One Colour and Two Colour tasks). Search arrays were preceded by spatially non-predictive colour singleton cues. Behavioural spatial cueing effects indicative of attentional capture were elicited only by target-matching but not by distractor-colour cues. However, when search displays contained one target-colour and one distractor-colour object among grey nontargets, N2pc components were triggered not only by target-colour but also by distractor-colour cues both in the One Colour and Two Colour task, demonstrating that task-set nonmatching items attracted attention. When search displays contained six items in six different colours, so that participants had to adopt a fully feature-specific task set, the N2pc to distractor-colour cues was eliminated in both tasks, indicating that nonmatching items were now successfully excluded from attentional processing. These results demonstrate that when observers adopt a feature-specific search mode, attentional task sets can be configured flexibly for multiple features within the same dimension, resulting in the rapid allocation of attention to task-set matching objects only.

Keywords: selective attention; top-down control; N2pc component; attentional capture; spatial cueing; event-related potentials

Search for known visual target objects is controlled by representations of their featural properties, such as colour, size, shape, or orientation. These representations have been described as attentional templates (e.g., Duncan & Humphreys, 1992), attentional control sets (e.g., Folk, Remington, & Johnston, 1992), or top-down task sets (e.g., Eimer & Kiss, 2008). Once a particular attentional control set is activated, stimuli with features that match this set will attract attention, while stimuli with non-matching features do not. This has been demonstrated in behavioural spatial cueing experiments where search displays containing a target object among distractor stimuli were preceded by task-irrelevant spatially uninformative cue displays. Cue items that matched one of the target-defining features captured attention, as reflected by faster reaction times (RTs) to subsequent targets that appeared at the same location as the matching cue as compared to targets at other uncued locations (e.g., Folk et al., 1992). In contrast, cues that did not match the currently active task set did not attract attention, even when these cues were physically salient feature singletons (e.g., Folk & Remington, 1998; Eimer & Kiss, 2008).

Such task-set contingent attentional capture effects have been demonstrated for target-defining features from different dimensions such as colour, size, motion, or object onsets or offsets, indicating that specific features from these dimensions can all be represented in a top-down task set. What is less clear, however, is whether such task sets can only represent one target feature at a time, or whether multiple target-defining features can be specified simultaneously. Studies that have investigated whether it is possible to activate an attentional control set for multiple colours have produced inconclusive results. Targets that are defined by a unique colour are detected easily during visual search, whereas the detection of colour conjunction targets (e.g., red/blue targets among blue/green and red/green distractors) is highly inefficient (Wolfe et al., 1990). Such observations have led to the suggestion that attentional target selection can be guided by only one feature from a particular dimension at a time (e.g., Wolfe, 2007). Along similar lines, Dombrowe, Donk, and Olivers (2011) found that sequential eye movements to two colour-defined targets were slower and more error-prone when these targets differed in their colour than when their colour is identical, thereby demonstrating the difficulty of maintaining two colour-specific attentional sets simultaneously (see also Meneer, Cave, & Donnelly, 2009; Stroud, Meneer, Cave, Donnelly, & Rayner, 2011, for similar observations of impaired performance during

single-colour relative to multiple-colour search). However, others have disputed the claim that attentional control can be set for more than one feature simultaneously. For example, Moore and Weissman (2010) found that the detection of target letters in two possible colours in a RSVP stream was impaired when these targets were preceded by lateral distractors that matched either of the two target colours, but not by nonmatching colour distractors. This observation indicates that both colour-matching distractors were able to capture attention in a task-set dependent fashion, which suggests that more than one colour-specific task set can be active at the same time (see also Beck, Hollingworth, & Luck, 2012, for similar conclusions based on the comparison of eye tracking data during single-colour versus multiple-colour search, and Adamo, Pun, Pratt, & Ferber, 2008, for evidence that task sets for different target colour/location combinations can be activated in parallel).

Irons, Folk, and Remington (2012) have provided the strongest evidence to date in support of the view that attention can be set simultaneously for multiple target colours. In a series of spatial cueing experiments, participants searched for either of two coloured targets (e.g., red or green items) in search arrays where a target was presented together with a task-irrelevant colour distractor (e.g., a blue item). Search arrays were preceded by cue arrays that contained one coloured item among three white items. The four items in the cue array appeared at the same locations as the target and distractors in the search arrays, but the location of the coloured cue item did not predict target location in the subsequent search array. On different trials, the colour cue either matched one of the two target colours (e.g., red or green) or the distractor colour (e.g., blue). As in previous cueing studies (e.g., Folk et al., 1992), behavioural spatial cueing effects (i.e., faster RTs to targets at cued versus uncued locations) were measured to test whether attention was captured by a particular colour cue, thereby facilitating responses to subsequent targets at the same location. As all colour cues appeared among three white items in the cue displays, they were perceptually salient feature singletons, and may thus have captured attention in a bottom-up involuntary fashion, regardless of whether they matched one of the target colours or the distractor colour. If this was the case, behavioural spatial cueing effects indicative of attentional capture should have been triggered both by target-matching and by distractor-matching cues. However, this was not the pattern of results found by Irons et al. (2012). Faster RTs for targets at cued versus uncued locations were found only for trials where the cue matched

one of the two target colours. Critically, no such spatial cueing effects were present on trials where the cue matched the distractor colour. This suggests that in spite of their physical salience, distractor-matching cues did not attract attention. Irons et al. (2012) interpreted these results as evidence that observers can adopt a simultaneous task set for two different colours, while simultaneously excluding other colours from this attentional task set (see also Folk et al., 1992, for similar task-set contingent attentional capture effects in tasks where participants searched for one particular target colour). Importantly, they also demonstrated that spatial cueing effects were present for target-matching colour cues and absent for distractor-matching cues even when these cues were not linearly separable in colour space (e.g., when participants searched for red or green targets and distractors were yellow-orange; Irons et al., 2012, Exp. 3). This suggests that a colour-specific top-down attentional control set can include both red and green and exclude yellow-orange, even though yellow-orange occupies an intermediate position in colour space between red and green.

The pattern of task-set contingent attentional capture effects observed by Irons et al. (2012) pose a strong challenge for the hypothesis that exactly one colour-specific attentional control setting can be active at any time (e.g., Wolfe et al., 1990, 2007). However, the absence of behavioural spatial cueing effects for distractor-matching cues reported by Irons et al. (2012) does not necessarily imply that these cues were unable to attract attention. For example, attention could initially have been allocated both to target-matching and distractor-matching cues, but might then be withdrawn from cues that do not match one of the two currently task-relevant colours (see Theeuwes, Atchley, & Kramer, 2000, for an analogous argument). If this was the case, the absence of cueing effects for distractor-matching cues would not reflect the absence of attentional capture by these cues, but instead the involvement of additional control processes at stages that follow the initial allocation of attention to both types of cues (e.g., Adamo, Pun, & Ferber, 2010). If multiple colour-specific control settings operate through a relatively slow disengagement of attention from nontarget-colour objects, evidence for the existence of such settings should only be obtained in paradigms that provide sufficient time for such attentional de-allocation processes to take place. This is the case when cues or distractors *precede* response-relevant target objects (e.g., Moore & Weissman, 2010; Irons et al., 2012), and behavioural effects indicative of multiple-feature attentional control are indeed found under such conditions. In

contrast, support for single-feature attentional control typically comes from single-frame visual search experiments without such temporal asynchronies (e.g., Wolfe et al., 1990; Houtkamp & Roelfsema, 2009; Dombrowe et al., 2011).

This possibility that during multiple-colour search, distractor-colour cues remain able to attract attention can be tested with event-related brain potential (ERP) measures, which offer temporally precise markers of attentional selection processes. To assess the time course of attentional capture by target-matching and nonmatching colour cues when a multiple-colour task set is active, the N2pc component is a particularly useful tool, because this component is an established electrophysiological marker of the spatially selective attentional processing of candidate target objects in extrastriate visual areas. The N2pc is an enhanced negativity that is triggered at posterior scalp electrodes contralateral to targets that are presented among distractor objects in visual search arrays. This component typically emerges between 180 ms and 200 ms after stimulus onset of visual arrays that contain a candidate target item, and is assumed to reflect the attentional selection of task-set matching objects (Luck & Hillyard, 1994; Eimer, 1996; Woodman & Luck, 1999; Mazza, Turatto, Umiltà, & Eimer, 2007). Previous ERP studies of task-set contingent attentional capture have demonstrated that the N2pc can be used to measure currently active top-down attentional control settings. During search for a specific target feature, task-set matching colour singleton cues (e.g., red singleton cues during search for red targets) triggered an N2pc, but nonmatching cues did not (e.g., red singleton cues during search for blue targets or small targets; e.g., Eimer & Kiss, 2008; Lien, Ruthruff, Goodin, & Remington, 2008; Leblanc, Prime, & Jolicoeur, 2008; Eimer, Kiss, Press, & Sauter, 2009). The presence of an N2pc to target-matching cues shows that these cues capture attention at a relatively early stage of visual-perceptual processing, while the absence of an N2pc to nonmatching cues indicates that their features fail to capture attention because they are not part of the currently active task set.

In a recent study (Grubert & Eimer, 2013) we employed the N2pc component to compare the efficiency of top-down attentional control during single-colour versus multiple-colour search. Observers had to select and identify colour-defined target digits that were accompanied by a single grey nontarget object in the opposite visual field. RTs were about 30 ms slower in blocks in which the target was defined by one out of two possible colours

(Two Colour task) than in blocks where all targets were defined by the same colour (One Colour task), and this RT difference was matched by a corresponding onset delay of N2pc components to targets during two-colour as compared to single-colour search. On some trials, search arrays contained a grey nontarget and a distractor-colour item, which had to be ignored. These distractor-colour items triggered an N2pc indicative of attentional capture during two-colour search, even though they were task-irrelevant. In contrast, no distractor-colour N2pc was observed during single-colour search. These observations suggest that attentional control processes responsible for the selection of targets and the rejection of non-target objects operate more efficiently when observers can adopt a single-colour task set than during multiple-colour search. This does however not necessarily imply that only a single colour-specific attentional task set can be active at any moment in time, and that attentional object selection cannot be controlled at all by multiple-colour task sets. In our previous study (Grubert & Eimer, 2013), the N2pc to distractor-colour objects in the Two Colour task was smaller and emerged later than the N2pc to target-colour items, demonstrating that attention was not completely colour-unselective in this task.

Unambiguous electrophysiological evidence for the existence of multiple-colour task sets comes from another recent N2pc study (Grubert & Eimer, 2015) where participants had to select two colour-defined targets in two displays that were presented in rapid succession, with stimulus onset asynchronies (SOAs) of either 100 ms or 10 ms. In both displays, the target item was accompanied by a nontarget in a different task-irrelevant colour on the opposite side. When the two targets were defined by the same constant colour (One Colour task), N2pc components to targets in the first and second display were equal in size and their onset latency difference closely matched the objective SOA between the two displays. This suggests that both targets were selected rapidly and in parallel, with each selection process following its own independent time course (see also Eimer & Grubert, 2014). Critically, a very similar pattern of N2pc results was observed in a Two Colour task where the two successive target objects always had different colours, which appeared unpredictably in the first or second display. Relative to the objective SOA time, separating the two displays, latency differences between first and second target N2pc components were only increased by about 15-20 ms, demonstrating that attention could still be allocated very rapidly to both target colours. These observations appear inconsistent with the hypothesis that attentional

selection processes in the Two Colour task were based on a slow serial switch between different colour-specific task sets, and suggest instead that top-down task settings can represent multiple target colours simultaneously.

The goal of the current study was to use the N2pc component as a marker of attentional capture in spatial cueing tasks that closely matched the setup of Irons et al. (2012) to further investigate the question whether attentional selection processes can be controlled effectively by simultaneous top-down task sets for different colours. In Experiment 1, participants searched for either of two possible colour-defined targets (e.g., red or green bars) that were presented among grey nontarget objects. As in the experiments by Irons et al. (2012), all search arrays also contained a task-irrelevant distractor-colour item (e.g., a blue bar, see Figure 1). Search arrays were preceded by cue arrays that contained a colour singleton item. This coloured item could match one of the two target colours or the distractor colour, and all three cue colours were equiprobable. Because the locations of the colour cue and the subsequent target-colour bar were uncorrelated, colour cues were spatially uninformative with respect to target location. While the cue and target arrays in the Irons et al. (2012) experiment contained four items, these displays included six items in the present study (two items each on the left and right side, and two at the top and bottom positions). To maximize the number of trials available to compute N2pc components to lateralized colour cues, these cues and the target-colour and distractor-colour objects in the subsequent search arrays always appeared at one of the four positions on the left and right, and never at the top or bottom positions. The stimulus onset asynchrony (SOA) between cue and target arrays was slightly longer than in the Irons et al. (2012) experiments (200 ms as compared to 150 ms), to allow the measurement of cue-elicited N2pc components that are uncontaminated by any ERP activity triggered in response to the subsequent target array.

We expected to confirm the behavioural effects reported by Irons et al. (2012). Target-matching colour cues should trigger spatial cueing effects indicative of task-set contingent attentional capture (i.e., faster RTs for targets at cued versus uncued locations). In contrast, no such effect should be found for nonmatching colour cues, in spite of the fact that these cues were also colour singletons and therefore just as salient as target-matching cues. The absence of behavioural spatial cueing effects for distractor-matching cues was interpreted by Irons et al. (2012) as evidence that these cues did not attract attention

because their colour was not part of a currently active multiple-colour task set. If this interpretation is correct, N2pc components should be exclusively triggered in response to target-matching cues, but should be entirely absent for nonmatching cues. In contrast, the presence of an N2pc in response to nonmatching cues would show that task-irrelevant colours cannot be completely prevented from attracting attention during multiple-colour search. To preview the main findings, Experiment 1 did indeed reveal the presence of a reliable N2pc component to distractor-colour cues, in spite of the fact that the behavioural effects perfectly replicated the pattern reported by Irons et al. (2012). Experiment 2 was conducted to reconcile these apparently contradictory behavioural and N2pc results. To determine whether the presence of an N2pc to distractor-colour cues in Experiment 1 reflects a fundamental impairment in the control of attentional object selection during multiple-colour search, or is due to other aspects of the search task employed by Irons et al. (2012), Experiments 3 and 4 compared N2pc components to target-matching and nonmatching cues in One Colour and Two Colour search tasks, where the visual properties of the search displays were varied between these two experiments.

Experiment 1

Method

Participants. Twelve paid observers participated in Experiment 1 (aged 24 to 40 years; mean age 31 years). Seven were female; one was left handed. All participants reported normal or corrected-to-normal vision and colour vision.

---------- Figure 1 ----------

Stimuli and procedure. Stimuli were displayed on a 22-inch Samsung wide SyncMaster 2233 LCD monitor with a resolution of 1280x1024 pixels and a 100 Hz refresh rate. Participants were seated in a dimly illuminated cabin and viewed the screen at a distance of approximately 100 cm. Manual responses were registered on two purpose-built

response keys. Stimulus presentation, timing, and response recording were controlled by a LG Pentium PC running under Windows XP, using the Cogent 2000 toolbox (www.vislab.ucl.ac.uk/Cogent/) for MATLAB (Mathworks, Inc.).

Stimuli were presented against a black background. A grey fixation point (0.2° x 0.2°) was continuously present throughout each block. On each trial, a cue display preceded a search display. Both displays were presented for 50 ms and were separated by a 150 ms blank interval (200 ms SOA). Cue displays consisted of six sets of four closely aligned dots (0.8° x 0.8°). These items were presented at an eccentricity of 4° on a virtual circle at the 2, 4, 6, 8, 10, and 12 o'clock positions (see Figure 1). One of the cue items was coloured (red, green, or blue; CIE colour coordinates .628/.340, 268/.566, or .182/.181, respectively), the remaining five items were grey (323/.355). The colour cue appeared randomly at one of the four lateral positions, but never at the top or bottom positions. Search arrays contained six horizontally and vertically oriented bars (0.5° x 1.2°) at the same six locations as the items in the cue arrays. The orientation of each bar was randomly and independently selected for each trial. Each search array contained one of two possible target-colour bars and one distractor-colour bar among four grey bars. Target-colour and distractor-colour bars could only appear at one of the four lateral positions, so that the top and bottom positions in the search array were always occupied by grey nontargets. Participants were instructed to report the orientation of the target-colour bar by pressing a corresponding response key (top key: vertical target; bottom key: horizontal target) with the left or right index finger. The hand-to-key mapping was reversed after four of the eight experimental blocks. For each participant, there were two equiprobable target colours (red/blue, red/green, green/blue, counterbalanced across participants). The remaining colour was designated as distractor colour. All stimuli in the cue and search arrays were equiluminant (8.8 cd/m^2). The locations of the colour cue and the target-colour bar were selected independently on each trial, so that colour cues were spatially uninformative with respect to the location of the subsequent target-colour bar.

Participants completed eight blocks of 96 trials (divided in two sub-blocks containing 48 trials), resulting in 768 experimental trials in total. Each of the three cue colours was presented on 32 trials per block. Cues were followed by a target-colour bar at the same location on 8 trials and by a target-colour bar at one of the three uncued lateral locations on

24 trials. On trials with target-colour cues, one of the two possible target colours was independently selected for the cue array and for the subsequent search array. Therefore, colour singleton cues and target bars had the same colour (colour-match trials) or two different colours (colour-nonmatch trials) on half of all target-colour cue trials, respectively. Before the start of the experiment and after block 4 when response hands were swapped, participants completed a practice block containing 48 trials.

EEG recording and data analysis. The continuous EEG was DC-recorded from 23 scalp electrodes, was sampled at a rate of 500 Hz, and digitally low-pass filtered at 40 Hz. Electrodes were mounted in an elastic cap at standard positions of the extended 10/20 system. All electrodes were online referenced to the left earlobe and re-referenced offline to the average of both earlobes. After EEG acquisition, no further filters were applied. Trials with artefacts (eye movements exceeding ±30 µV in the HEOG channels; blinks exceeding ±60 µV at Fpz; muscular movements exceeding ±80 µV in all other channels) and with incorrect, anticipatory (faster than 200 ms), very slow (slower than 1200 ms), or absent responses were excluded from EEG analyses. Artefact rejection led to the exclusion of 3.3% of all target colour cue trials, and of 3.5% of all distractor colour cue trials. For the remaining trials, EEG was segmented from 100 ms before to 500 ms after cue onset, and was averaged relative to a 100 ms baseline prior to cue onset, separately for all combinations of cue type (target-colour, distractor-colour cue) and visual field of cue (left, right). N2pc components were quantified on the basis of mean amplitudes obtained in the 200-300 ms time window after cue onset at lateral posterior electrodes PO7 and PO8. N2pc onset latencies were determined with a jackknife-based procedure (Miller, Patterson, & Ulrich 1998; Ulrich & Miller, 2001). This procedure estimates onset latencies on the basis of grand averages computed from subsamples of averaged ERP difference waveforms obtained by successively excluding one participant from the original sample. N2pc onset latencies were computed separately for target-colour and distractor-colour cue trials and were defined as the point in time where the difference waveform for each subsample exceeded an absolute threshold value of -0.5 µV. The statistical values of the *t*-test comparing N2pc onset latencies were corrected according to the formula described by Miller et al. (1998), as indicated with the label 't_c'. All *t*-tests were two-tailed and Bonferroni corrected where necessary. Effect sizes

are reported in terms of partial eta squared for *F*-tests and *t*-tests on jackknifed means (labelled $\eta_p^2{}_c$) and Cohen's d, with a confidence interval of 95%, for all other *t*-tests. [1]

Results

---------- Figure 2 ----------

Behavioural results. The exclusion of trials with RTs below 200 ms or above 1200 ms resulted in the removal of less than 0.5% of all trials. Figure 2 (top left panel) shows mean correct RTs to targets at cued versus uncued locations, separately for target-colour cue and distractor-colour cue trials. Target-colour cue RTs are shown separately for trials where cue and target colours were identical (colour-match trials), and trials where they were different (colour-nonmatch trials). RT data were subjected to a repeated-measures ANOVA with the factors cue type (target-colour versus distractor-colour cues) and spatial cueing (targets at cued versus uncued positions). In this analysis, colour-match and nonmatch trials were collapsed. A main effect of spatial cueing, $F(1,11) = 22.2$, $p = .001$, $\eta_p^2 = .67$, demonstrated that RTs were generally faster to targets at cued as compared to uncued positions. Critically, there was an interaction between cue type and spatial cueing, $F(1,11) = 38.5$, $p < .001$, $\eta_p^2 = .78$, showing that spatial cueing effects indicative of attentional capture differed between target-colour cue and distractor-colour cue trials. Follow-up *t*-tests confirmed that there was a reliable spatial cueing effect of 38 ms on target-colour cue trials, $t(11) = 7.4$, $p < .001$, $d = .53$. In marked contrast, this effect was absent on distractor-colour cue trials, $t(11) < 1$.

A second ANOVA was conducted for target-colour cue trials only, and included the factors colour congruency (colour-match versus nonmatch between singleton cue and target bar) and spatial cueing. There was a significant effect of colour congruency, $F(1,11) = 21.1$, $p = .001$, $\eta_p^2 = .66$, as target RTs were faster on colour-match relative to nonmatch trials (525 ms versus 560 ms; see Figure 2). The interaction between colour congruency and spatial cueing was not reliable, $F(1,11) = 3.2$, $p = .103$, indicating that spatial cueing effects

[1] As there is no standardized formula to correct individual group means and standard deviations of jackknifed samples in order to calculate effect size measures such as Cohen's d, jackknifed group means of N2pc latency values were fed into one-way ANOVAs where the error variance can be corrected according to the formula described by Ulrich and Miller (2001) in order to calculate corrected partial eta squared values. For all t-tests on N2pc latency measures, effect sizes are reported as corrected partial eta squared (labelled $\eta_p^2{}_c$).

indicative of attentional capture by target-colour cues did not differ between colour-match (33 ms) and nonmatch trials (42 ms).

Response errors were infrequent (3.3% of all trials). An ANOVA of error rates with the factors cue type (target-colour versus distractor-colour cues) and spatial cueing revealed a significant interaction between these two factors, $F(1,11) = 4.9$, $p = .05$, $\eta_p^2 = .31$. On target-colour cue trials, errors were more frequent in response to uncued as compared to cued targets (4.4% versus 2.2%, $t(11) = 2.5$, $p = .031$, $d = .89$). On distractor-colour cue trials, there was no difference in error rates between uncued and cued targets (3.6% versus 3.1%, $t(11) < 1$). Error rates on target-colour cue trials were statistically the same on colour-match (3.3%) and nonmatch trials (3.4%), and there was no interaction between colour congruency and spatial cueing, both $F(1,11) < 1.3$, $p > .280$, indicating that the increase of error rates to uncued versus cued targets did not differ between colour-match (1.9%) and nonmatch trials (2.6%).

---------- Figure 3 ----------

N2pc components. Figure 3 (top panel) shows grand-average event-related potentials (ERPs) elicited at electrode sites PO7 and PO8 contra- and ipsilateral to target-colour and distractor-colour cues. A large N2pc component was triggered in response to target-colour cues. An N2pc also seems to be present for distractor-colour cues, although it was attenuated and delayed relative to the target-colour N2pc. This can be seen more clearly in the difference waveforms (Figure 3, bottom panel) obtained by subtracting ipsilateral from contralateral ERPs, separately for the two types of cues.

Statistical analyses confirmed these observations. A repeated-measures ANOVA was conducted on ERP mean amplitudes measured in the 200-300 ms time interval after cue onset with the factors cue type (target-colour versus distractor-colour cue) and laterality (electrode contralateral versus ipsilateral to the colour cue). A main effect of laterality, $F(1,11) = 29.4$, $p < .001$, $\eta_p^2 = .73$, was accompanied by an interaction between cue type and laterality, $F(1,11) = 24.5$, $p < .001$, $\eta_p^2 = .69$, confirming that the N2pc to target-colour cues was reliably larger than the N2pc to distractor-colour cues. However, and importantly, follow-up *t*-test comparing ipsi- and contralateral activity, demonstrated that an N2pc

component was triggered not just by target-colour cues (-1.8 μV), $t(11) = 5.8$, $p < .001$, $d = .38$, but also by distractor-colour cues (-0.7 μV), $t(11) = 3.7$, $p = .003$, $d = .15$. Onset latency analyses confirmed that the N2pc to target-colour cues emerged earlier (194 ms after cue array onset) than the N2pc to distractor-colour cues (232 ms; $t_c(11) = 5.1$, $p < .001$, $\eta_{p^2c} = .70$).

Discussion of Experiment 1

The behavioural results of Experiment 1 confirmed the findings reported by Irons et al. (2012). Spatial cueing effects indicative of attentional capture (i.e., faster RTs to targets at cued relative to uncued locations) were triggered by target-colour cues, but were completely absent for distractor-colour cue trials. As in Irons et al. (2012), there was also an effect of colour congruency on target-colour cue trials, with faster RTs on colour-match versus nonmatch trials. However, the fact that spatial cueing effects of the same size were elicited by target-colour cues on colour-match and nonmatch trials shows that the ability of these cues to attract attention did not differ between these two types of trials. It is therefore likely that the colour congruency effect reflects processes that follow the attentional selection of task-set matching stimuli. Colour cues might act as primes that facilitate the processing of colour-matching target bars, and/or the selection of responses to these bars in a spatially non-selective fashion irrespective of whether targets appear at cued or uncued locations (see also Irons et al., 2012, for similar suggestions).

According to Irons et al. (2012), the presence of behavioural capture effects for target-colour cues and the absence of such effects for distractor-colour cues demonstrate that multiple-colour search can be guided by simultaneous attentional control settings for different colours. These control settings successfully prevent attentional capture by nonmatching colour cues, even though they are perceptually salient feature singletons. However, the N2pc results obtained in Experiment 1 show that these conclusions may need to be reconsidered. As expected, the two target-colour cues triggered robust N2pc components, confirming that these cues did indeed capture attention. However, and critically, a reliable N2pc component was also elicited in response to distractor-colour cues (Figure 3). This observation is obviously inconsistent with the assumption that multiple-

colour task sets guide the allocation of attention in a fully colour-selective fashion in this task. In this case, colour cues that do not match one of the target colours should be unable to attract attention and should therefore not trigger an N2pc component. The presence of an N2pc to distractor-colour cues in Experiment 1 demonstrates that task-set contingent top-down attentional control was not perfect, because a distractor colour was able to attract attention to some degree. The fact that the N2pc to distractor-colour cues was attenuated and delayed relative to the N2pc observed in response to target-colour cues (Figure 3) suggests that while task-set contingent attentional selectivity was not fully colour-selective, the attentional set for multiple colours still had some impact on the rapid allocation of attention, as reflected by the N2pc, with stronger capture by target-matching cues.

The observation that an N2pc component was triggered by distractor-colour cues in Experiment 1 may indicate fundamental limitations in the ability of multiple-colour attentional task sets to control the allocation of attention. However, another possibility is that some aspects of the specific task procedure developed by Irons et al. (2012) are responsible for the presence of residual attentional capture effects of distractor-colour cues, as reflected by the presence of N2pc components by these cues. These alternative hypotheses will be tested in Experiments 3 and 4. Another issue that needs to be addressed first is the striking dissociation between behavioural and electrophysiological markers of attentional capture observed in Experiment 1. Whereas the behavioural cueing effects suggest effective task-set dependent attentional control during multiple-colour search, the N2pc results demonstrate less-than-optimal top-down control, with attention being captured by both task-set matching and nonmatching cues. Experiment 2 was conducted to reconcile these apparently contradictory findings.

Experiment 2

It is possible that the cue-induced N2pc components and the behavioural spatial cueing effects observed in Experiment 1 are generated at different stages of attentional processing. Attention may initially be attracted by both matching and nonmatching cues, but may then be rapidly withdrawn from items that do not match the currently active multiple-

colour task set. In Experiment 2, we investigated this two-stage hypothesis by reducing the temporal interval between cue and search arrays. With a shorter cue-target SOA, search arrays may already be processed during the time where attention has not yet been withdrawn from nonmatching cues. As a result, behavioural spatial cueing effects should no longer be restricted to target-colour cues, but should also be found for distractor-colour cues. An analogous logic was applied in a previous study by Theeuwes et al. (2000) who investigated how search for a shape-defined target was affected by the presence of a task-irrelevant colour singleton object. When these two items appeared simultaneously in the same search display, target RTs were delayed relative to displays without a colour singleton. When the colour singleton appeared 150 ms prior to the target, no such interference effects were observed, suggesting that attention was rapidly de-allocated from the task-irrelevant singleton object.

The task procedures used in Experiment 2 were the same as in Experiment 1, except that the SOA between the cue and the search arrays was reduced from 200 ms to 100 ms. As this SOA is too brief to record cue-triggered N2pc components independent of ERP activity elicited by subsequent search arrays, only behavioural performance was measured. By bringing cue and search arrays into closer temporal proximity, target processing may coincide with the phase where attention has not yet been deallocated from nonmatching cues, and this should result in reliable spatial cueing effects on distractor-colour cue trials.

Method

Participants. Twelve different participants were paid to participate in Experiment 2 (aged 24-39 years; mean age 29 years). Seven were female; two were left handed. All participants reported normal or corrected-to-normal vision and colour vision.

Stimuli and procedure. These were the same as in Experiment 1, except that the SOA between cue and target arrays was reduced from 200 ms to 100 ms, and that no EEG was recorded during task performance. Cue and search displays were presented for 50 ms each, and were now separated by a 50 ms blank interval.

Results

As in Experiment 1, trials with anticipatory or very slow RTs were excluded from analysis (less than 1% of all trials). Figure 2 (bottom left panel) shows mean correct RTs to targets at cued versus uncued locations, separately for colour-matching and nonmatching target-colour cue trials, and for trials with distractor-colour cues. A repeated-measures ANOVA with the factors cue type (target-colour cues, collapsed across colour-matching and nonmatching trials, versus distractor-colour cues) and spatial cueing (targets at cued versus uncued positions) obtained a main effect of spatial cueing, $F(1,11) = 186.6$, $p < .001$, $\eta_p^2 = .94$, as RTs were generally faster to targets at cued as compared to uncued positions. As in Experiment 1, there was an interaction between cue type and spatial cueing, $F(1,11) = 21.6$, $p = .001$, $\eta_p^2 = .66$, demonstrating that spatial cueing effects indicative of attentional capture were larger for target-colour as compared to distractor-colour cues (48 ms versus 18 ms). However, and in contrast to Experiment 1, spatial cueing effects were now not only present on target-colour cue trials, $t(11) = 9.5$, $p < .001$, $d = .59$, but were also significant on distractor-colour cue trials, $t(11) = 6.6$. $p < .001$, $d = .25$.

In the ANOVA conducted for target-colour cue trials only, which included the factors colour congruency (match versus nonmatch of cue and target colours) and spatial cueing, there was a main effect of colour congruency, $F(1,11) = 42.3$, $p < .001$, $\eta_p^2 = .79$, with faster RTs on colour-match trials (545 ms) relative to nonmatch trials (597 ms; see Figure 2). As in Experiment 1, the interaction between colour congruency and spatial cueing was not reliable, $F(1,11) = 2.0$, $p = .189$, suggesting that that spatial cueing effects did not differ between colour-match and nonmatch trials (41 ms versus 56 ms). Response errors occurred on 3.5% of all trials. There were no main effects of cue type (target-colour cue: 3.5%, distractor-colour cue: 3.6%) or spatial cueing, and no significant interactions between these two factors for error rates, all $F(1,11) < 3.9$, $p > .078$. As for Experiment 1, error rates were the same on target-colour match (3.0%) and nonmatch trials (3.9%), and there was no interaction between colour congruency and spatial cueing, both $F(1,11) < 2.3$, $p > .164$, reflecting similar effects of spatial cueing on error rates in colour-match (1.5%) and nonmatch trials (1.8%).

Planned comparisons of RT spatial cueing effects obtained in Experiments 1 and 2 found no differences in the size of these effects for target-colour cue trials (38 ms versus 48 ms in Experiment 1 and 2, respectively; $t(11) = 1.7$, $p = .113$). In contrast, the spatial cueing effect on distractor-colour cue trials in Experiment 2 was significantly larger than the small RT difference between cued and uncued targets in Experiment 1 (18 ms versus 4 ms; $t(11) = 2.4$, $p = .037$, $d = .98$).

Discussion of Experiment 2

When the SOA between cue and target arrays was reduced to 100 ms, distractor-colour cues elicited reliable RT spatial cueing effects indicative of attentional capture. The fact that no such effects were observed in Experiment 1 with an SOA of 200 ms suggests that the temporal separation between cue and target arrays is critical for determining whether task-set nonmatching colour cues produce behavioural attentional capture effects during multiple-colour search. This pattern of results is also consistent with previous findings by Theeuwes et al. (2000), who demonstrated that presenting a task-irrelevant colour singleton 150 ms prior to a target is sufficient to eliminate the interference effects caused by this object. These findings support the hypothesis that the control of colour-based attentional selectivity includes two temporally distinct stages, with rapid attentional capture by all colour cues followed by a withdrawal of attention from cues that do not match the currently active task set. The observation that the spatial cueing effects triggered by distractor-colour cues were substantially smaller than the effects observed for target-colour cues is in line with the N2pc amplitude and latency differences between these two types of cues observed in Experiment 1. As in Experiment 1 and in the study by Irons et al. (2012), an effect of colour congruency was found for target-colour cues in Experiment 2, with faster RTs on trials where cue and target colours were identical relative to colour-nonmatch trials. Again, cue-induced attentional capture was not modulated by colour congruency, suggesting that this factor affects processing stages that follow the allocation of attention to target-colour objects.

Experiment 2 has demonstrated that evidence for attentional capture by task-set nonmatching colour cues during multiple-colour search can not only be obtained with electrophysiological measures, but can also be demonstrated behaviourally, provided that

temporal parameters are set appropriately for such behavioural effects to emerge. It is therefore essential to determine whether these capture effects reflect a general limitation in the selectivity of attentional control during multiple-colour search, or are instead linked to a more specific aspect of the colour search task used by Irons et al. (2012) and in the present study.

Experiment 3

If the presence of attentional capture effects by distractor-colour cues observed in Experiments 1 and 2 reflects a limitation in the selectivity of top-down control processes that is specific to multiple-colour search tasks, no such effects should be observed when observers search for targets that are defined by a fixed single colour. To test this prediction, Experiment 3 directly compared the pattern of N2pc components to target-colour and distractor-colour cues between a Two Colour search task that was identical to Experiment 1 and a new One Colour search task where participant searched for a single target colour that remained constant throughout. As in Experiment 1, search displays contained one target-colour object and one distractor-colour object among four grey items, and the SOA between cue and target arrays was 200 ms. The results from the Two Colour task should confirm the observations from Experiment 1, with a significant albeit attenuated and delayed N2pc to distractor-colour cues, but no behavioural spatial cueing effects for these cues. If attentional control was fully colour-selective in the One Colour task where it could be guided by a fixed task set for a single target colour, no N2pc should be elicited by distractor-colour cues in this task.

Method

Participants. Sixteen new participants were paid to participate in Experiment 3. Four of them were excluded due to exceedingly heavy eye activity during the experiment. The remaining twelve participants were aged 24 to 39 years (mean age 32 years). Six were

female; three were left handed. All participants reported normal or corrected-to-normal vision and colour vision.

Stimuli and procedure. The Two Colour task was identical to Experiment 1. In the One Colour task, search displays always contained the same colour target, one distractor-colour item, and four grey items. The cue displays either contained a cue item in the current target colour or an item in the distractor colour among five grey items. Red, green, and blue served as possible target and distractor colours in both tasks. In the Two Colour task, four participants searched for red or blue targets, another four for red or green targets, and the remaining four participants for green or blue targets. The remaining colour was assigned as distractor colour. In the One Colour task, the distractor colour was identical to the distractor colour used in the Two Colour task for each participant. The target colour was one of the two colours that served as target colour in the Two Colour task. For each specific target colour combination in the Two Colour task, either of these two colours was the target colour for two participants.

The two tasks were each presented in successive blocks, and task order was counterbalanced across participants. The Two Colour task comprised six blocks of 96 trials (divided into two sub-blocks of 48 trials), resulting in a total of 578 experimental trials. In the One Colour task, participants completed four blocks of 96 trials (divided into two 48 trial sub-blocks), resulting in 512 experimental trials. Each of the two cue colours (target and distractor colour) was presented on 48 trials per block and was followed by a target at the same location as the cue on 12 trials and by an uncued target on 36 trials.

EEG recording and data analysis. These were identical to Experiment 1, except that task (One Colour versus Two Colour) was included as an additional factor. Onset latency analyses for N2pc components now also included an ANOVA with the factors task and cue type, and *F*-values as well as the effect sizes, were corrected according to the formula by Ulrich and Miller (2001; labelled as F_c and $\eta_p^2{}_c$, respectively). Rejection rates of trials contaminated with artefacts in Experiment 3 were 2.4% on target colour and 4.1% on distractor colour cue trials in the One Colour task and 3.4% on target colour and 3.1% on distractor colour cue trials in the Two Colour task.

Results

Behavioural results. Trials with fast (< 200 ms) and slow (> 1200 ms) responses were excluded from analysis (less than 0.5% of all trials). Figure 2 (top right panel) shows mean correct RTs to targets at cued versus uncued locations in the One Colour and Two Colour tasks, separately for trials with target-colour and distractor-colour cues. Because colour congruency (match versus nonmatch of target-colour cue and target) did not affect spatial cueing effects in Experiments 1 and 2, and because this variable was not manipulated in the One Colour task where target-colour cues and targets always matched, this factor was not included in the analyses of behavioural data. RTs on target-colour cue trials in the Two Colour task were averaged across colour-match and nonmatch trials. A repeated-measures ANOVA with the factors cue type (target-colour versus distractor-colour cues), spatial cueing (targets at cued versus uncued positions), and task (One Colour versus Two Colour task) obtained a main effect of task, $F(1,11) = 12.5$, $p = .005$, $\eta_p^2 = .53$, with faster RTs in the One Colour as compared to the Two Colour task (504 ms versus 535 ms). There was also a main effect of spatial cueing, $F(1,11) = 34.2$, $p < .001$, $\eta_p^2 = .76$, as RTs were generally faster to targets at cued versus uncued positions. An interaction between cue type and spatial cueing, $F(1,11) = 58.4$, $p < .001$, $\eta_p^2 = .84$, again showed task-set contingent spatial cueing effects which were significant for target-colour cues (39 ms, $t(11) = 8.7$, $p < .001$, $d = .57$), but absent for distractor-colour cue trials (-7 ms, $t(11) = 1.9$, $p = .086$). Critically, there was no three-way interaction between task, cue type, and spatial cueing, $F(1,11) < 1$, demonstrating that these task-set contingent attentional capture effects were identical in the One Colour and Two Colour tasks.

A similar pattern was observed for error rates. There was a main effect of spatial cueing, $F(1,11) = 6.5$, $p = .027$, $\eta_p^2 = .37$, reflecting more errors for targets at uncued locations, that interacted with cue type, $F(1,11) = 7.8$, $p = .017$, $\eta_p^2 = .42$. On target-colour cue trials, errors were more frequent in response to uncued as compared to cued targets (4.1% versus 1.2%, $t(11) = 3.0$, $p = .012$, $d = 1.28$). On distractor-colour cue trials, there was no difference between uncued and cued targets (2.3% versus 2.5%, $t(11) < 1$). This task-set

contingent modulation of spatial cueing effects on error rates did not differ between the One Colour and Two Colour tasks, $F(1,11) = 1.1$, $p = .311$).

N2pc components. Figure 4 (top and middle panel) shows grand-average event-related potentials (ERPs) elicited at electrode sites PO7 and PO8 contra- and ipsilateral to target-colour and distractor-colour cues, separately for the One Colour and Two Colour tasks. In both tasks, large N2pc components were triggered to target-colour cues. More importantly, smaller and delayed N2pc components to distractor-colour cues appear to be present not only in the Two Colour task, but also in the One Colour task. This can be seen more clearly in the contralateral-ipsilateral N2pc difference waveforms, which shows a very similar pattern of N2pc components to target-colour and distractor-colour cues in both tasks. Critically, the N2pc to distractor-colour cues appears to be virtually identical in the One Colour and Two Colour tasks (Figure 4, bottom right panel).

Statistical analyses confirmed these observations. A repeated-measures ANOVA was conducted on ERP mean amplitudes measured at PO7/8 in the 200-300 ms time interval after cue onset with the factors cue type (target-colour versus distractor-colour cue), laterality (electrode contralateral versus ipsilateral to the colour cue), and task (One Colour versus Two Colour task). A main effect of laterality, $F(1,11) = 78.4$, $p < .001$, $\eta_p^2 = .88$, was accompanied by an interaction between cue type and laterality, $F(1,11) = 151.0$, $p < .001$, $\eta_p^2 = .93$, confirming that the N2pc to target-colour cues was reliably larger than the N2pc to distractor-colour cues. There was no interaction between cue type, laterality, and task, $F(1,11) = 2.6$, $p = .134$, demonstrating that this task-set contingent modulation of N2pc amplitudes was equivalent in both tasks. Follow-up *t*-tests were conducted separately for all cue types. In the Two Colour task, reliable N2pc components were present not only for target-colour cues (-1.9 µV), $t(11) = 9.6$, $p < .001$, $d = .62$, but also for distractor-colour cues (-0.8 µV), $t(11) = 5.6$, $p < .001$, $d = .23$, confirming the observations from Experiment 1. Critically, the same pattern was found for the One Colour task, with significant N2pc components to target-colour (-2.2 µV), $t(11) = 9.9$, $p < .001$, $d = .58$, as well as distractor-colour cues (-0.7 µV), $t(11) = 4.4$, $p = .001$, $d = .17$. A direct comparison of N2pc components to distractor-colour cues between the One Colour and Two Colour tasks confirmed the absence of any amplitude difference, $t(11) < 1$.

N2pc onset latencies were analysed with a repeated-measures ANOVA with the factors task and cue type. There was a main effect of cue type, $F_c(1,11) = 56.7$, $p < .001$, $\eta_p{}^2{}_c = .84$, confirming that N2pc components emerged later to distractor-colour cues as compared to target-colour cues (231 ms versus 185 ms). There was no interaction between task and cue type, $F_c(1,11) < 1$, confirming that this task-set dependent N2pc onset difference was equivalent for the One and Two Colour tasks.

Discussion of Experiment 3

The results from the Two Colour task of Experiment 3 confirmed the findings of Experiment 1. Behavioural spatial cueing effects indicative of attentional capture were only present for target-colour cues but not for distractor-colour cues. However, reliable N2pc components were triggered by target-colour as well as by distractor-colour cues. Even though N2pcs to distractor-colour cues were smaller and delayed relative to N2pc components elicited by target-colour cues, their presence demonstrates that task-set nonmatching colour cues attracted attention to some degree in the Two Colour task. If this was due to an impaired selectivity of attentional control processes during multiple-colour search, no N2pc components should be triggered by distractor-colour cues in the One Colour task, where target selection could be guided by a single attentional task set for one constant target colour. In fact, the pattern of N2pc components to target-colour and distractor-colour cues was very similar in the One Colour and Two Colour tasks. Distractor-colour cues elicited virtually identical N2pcs in both tasks, which shows that these cues were able to attract attention regardless of whether participants searched for a single colour or two possible target colours. These observations show that the presence of N2pc components to distractor-colour cues in the Two Colour task should not be interpreted as evidence for an impairment of attentional selectivity that is specific to multiple-colour search.

If this is the case, a different aspect of the experimental procedures used by Irons et al. (2012) and in the current Experiments 1 to 3 must be responsible for the residual ability of distractor-colour cues to capture attention, regardless of whether a single colour or two different colours are currently task-relevant. Previous research has shown that when search targets are feature singletons, participants may not activate an attentional task set for a

particular feature value, but instead search for any feature discontinuity in a search display ("singleton search mode", e.g., Bacon & Egeth, 1994; Folk & Anderson, 2010; Irons et al., 2012, Exp.1; see also Eimer & Kiss, 2010, for corresponding N2pc evidence). During singleton search, colour singleton cues will capture attention regardless of whether they match the currently relevant target colour(s) or not. The search displays used by Irons et al. (2012) and in Experiments 1 to 3 of the current study included not only the target-colour item but also another object in a different distractor colour. The rationale for this was to ensure that the target was not the only coloured item in a search display, so that participants would adopt a feature search mode and search for specific target features rather than for any colour singleton, regardless of its value. However, the possibility remains that including an additional distractor colour object among other uniform items may not have been sufficient to suppress a singleton search mode entirely, and that this may be responsible for the residual ability of distractor-colour cues to attract attention. To test this hypothesis, Experiment 4 employed heterogeneous search displays that included six items in six different colours.

Experiment 4

If the presence of N2pc components to distractor-colour cues in Experiments 1 and 3 was the result of participants' search being guided at least in part by a feature-unspecific singleton search mode, these cues should no longer elicit N2pc components under conditions where singleton search is no longer possible for the guidance of attention towards target objects. In Experiment 4, search displays contained six objects in six different colours, and participants searched for one or two possible target colours in the One Colour and Two Colour tasks. Such heterogeneous search displays exclude the adoption of a singleton search mode, and participants should therefore employ a fully feature-specific task set for one or two target colours. Therefore, no N2pc should be triggered by distractor-colour cues in the One Colour task. In an earlier N2pc experiment (Eimer et al., 2009, Exp.1) where target-colour or nontarget-colour cues preceded heterogeneous search displays and participants searched for targets defined by one particular colour, N2pc components were

indeed only elicited by target-colour cues and not by singleton cues in a different nontarget colour. If feature-specific attentional task settings remain effective even when they specify two different target colours, as proposed by Irons et al. (2012), distractor-colour cues should also not be able to attract attention during multiple-colour search with heterogeneous search displays. These cues should therefore no longer elicit an N2pc component in the Two Colour task of Experiment 4.

Method

Participants. Fourteen new observers participated in Experiment 4 and received monetary compensation. Two of them were excluded from the sample due to exceptionally heavy blinking during the experiment. The remaining twelve participants were aged 24 to 41 years (mean age 31 years). Five were female; two were left handed. All participants reported normal or corrected-to-normal vision and colour vision.

Stimuli and procedure. The One and Two Colour tasks were identical to Experiment 3, except for the fact that three of the four grey items in each search display were replaced by three different colours. These colours were yellow (CIE colour coordinates .422/.468), magenta (.289/.168), and cyan (.212/.350). To achieve equiluminance (~10.2 cd/m^2) for this new set of six colours, the red, green, blue and grey colour coordinates slightly differed from the ones used in Experiments 1 to 3 (red: .627/.336, green: .263/.568, blue: .189/.193, and grey: .323/.252). As in the previous experiments, red, green and blue served as target or distractor colours and this was balanced across participants. Search displays therefore always contained one search bar in the target colour (One Colour task) or in one of the two possible target colours (Two Colour task), one bar in the distractor colour (which could also appear in the distractor cue display), and four bars in four different nontarget colours (yellow, magenta, cyan and grey) that were assigned randomly and individually on each trial. As a result, each search display now contained six items in six different colours (see Figure 1). As in Experiment 1 to 3, cue displays contained a colour singleton among five grey items, which either matched the target colour(s) or the distractor colour.

EEG recording and data analysis. These were identical to Experiment 3. 7.8% and 7.7% of all target-colour and distractor-colour cue trials were removed due to artefacts in the One Colour task. In the Two-Colour task, 2.7% and 11.9% of these trials were removed.

Results

Behavioural results. Fast (< 200 ms) and slow (> 1200 ms) responses were excluded from analysis (less than 0.6% of all trials). Figure 2 (bottom right panel) shows mean correct RTs to targets at cued versus uncued locations in the One Colour and Two Colour tasks, separately for trials with target-colour and distractor-colour cues. RTs on target-colour cue trials in the Two Colour task were averaged across trials where cue and target colours matched or did not match. A repeated-measures ANOVA with the factors cue type (target-colour versus distractor-colour cues), spatial cueing (targets at cued versus uncued positions), and task (One Colour versus Two Colour task) obtained a main effect of task, $F(1,11) = 28.6$, $p < .001$, $\eta_p^2 = .72$, with faster RTs in the One Colour as compared to the Two Colour task (508 ms versus 587 ms). A main effect of spatial cueing, $F(1,11) = 12.9$, $p = .004$, $\eta_p^2 = .54$, reflected faster RTs to targets at cued versus uncued positions. As before, an interaction between cue type and spatial cueing, $F(1,11) = 40.7$, $p < .001$, $\eta_p^2 = .79$, was due to the task-set contingency of spatial cueing effects, which were present for target-colour cues (41 ms, $t(11) = 9.2$, $p < .001$, $d = .74$), but absent for distractor-colour cue trials (-8 ms, $t(11) = 1.1$, $p = .301$). Critically, there was no three-way interaction between task, cue type, and spatial cueing, $F(1,11) = 2.1$, $p = .172$, demonstrating that these task-set contingent attentional capture effects did not differ systematically between the One Colour and Two Colour tasks.

For error rates, there was a main effect of task, $F(1,11) = 5.7$, $p = .036$, $\eta_p^2 = .34$, with more errors in the Two Colour than in the One Colour task (5.2% versus 2.1%). The main effect of spatial cueing just failed to reach significance, $F(1,11) = 4.6$, $p = .056$, but there was an interaction between spatial cueing and cue type, $F(1,11) = 8.0$, $p = .017$, $\eta_p^2 = .42$. On target-colour cue trials, errors were more frequent for uncued versus cued targets (5.1% versus 2.4%, $t(11) = 2.7$, $p = .020$, $d = .89$). On distractor-colour cue trials, there was no such

difference (3.3% versus 3.8%, $t(11) = 1.2$, $p = .242$). There was no interaction between task, spatial cueing, and cue type, $F(1,11) < 1$.

N2pc components. Figure 5 (top and middle panel) shows grand-average event-related potentials (ERPs) elicited at PO7/8 contra- and ipsilateral to target-colour and distractor-colour cues, separately for the One Colour and Two Colour tasks. In both tasks, N2pc components were clearly present in response to target-colour cues. In contrast, these components appear to be absent in both tasks for distractor-colour cues. The contralateral-ipsilateral N2pc difference waveforms shown in Figure 5 (bottom panel) confirm the presence of large N2pc components to target-colour cues, and suggest that N2pcs to distractor-colour cues were either very small or absent in both tasks.

A repeated-measures ANOVA conducted on ERP mean amplitudes measured at PO7/8 in the 200-300 ms time interval after cue onset with the factors cue type (target-colour versus distractor-colour cue), laterality (electrode contralateral versus ipsilateral to the colour cue), and task (One Colour versus Two Colour task) obtained a main effect of laterality, $F(1,11) = 33.0$, $p < .001$, $\eta_p^2 = .75$, and an interaction between cue type and laterality, $F(1,11) = 24.8$, $p < .001$, $\eta_p^2 = .69$, reflecting the larger N2pc to target-colour versus distractor-colour cues. There was no interaction between cue type, laterality, and task, $F(1,11) = 1.8$, $p = .206$. Follow-up *t*-tests were conducted separately for all cue types. In the One Colour task, reliable N2pc components were present for target-colour cues (-1.7 μV), $t(11) = 5.8$, $p < .001$, $d = .31$. In contrast, and importantly, no significant N2pc was elicited in response to distractor-colour cues (-0.1 μV), $t(11) < 1$. The same pattern was found for the Two Colour task, with a significant N2pc component to target-colour cues (-1.5 μV), $t(11) = 5.4$, $p < .001$, $d = .27$, and no reliable N2pc to distractor-colour cues (-0.2 μV), $t(11) = 1.4$, $p = .186$.[2]

Comparison of N2pc components to distractor-colour cues between Experiments 3 and 4. The presence of significant N2pc components to distractor-colour cues in Experiment

[2] The N2pc difference waveforms in Figure 5 (bottom panel) suggest that there could be a small delayed N2pc to distractor-colour cues from approximately 240 ms after cue onset that may not be reliable when N2pc mean amplitudes are analysed within a wider 200-300 ms post-cue time window. To assess this possibility, we analysed ERP mean amplitudes elicited at PO7/8 on distractor-colour cue trials for a more narrow time window (240 – 290 ms). There were no significant N2pc components within this time window in either the One Colour or the Two Colour task, both $t(11) = 1.9$, $p > .092$.

3 and the absence of these components in Experiment 4 suggest that the change of search display properties between these two experiments determined the presence versus absence of rapid attentional capture by distractor-colour cues in the One Colour and Two Colour tasks. To demonstrate this more directly, additional analyses of N2pc amplitudes to these cues were conducted across experiments, with the within-subject factors laterality and the between-subject factor experiment (Experiment 3 versus Experiment 4), separately for the One Colour and Two Colour tasks. The interaction between laterality and experiment was significant both for the One Colour task, $F(1,22) = 6.4$, $p = .019$, $\eta_p^2 = .23$, and for the Two Colour task, $F(1,22) = 8.3$, $p = .009$, $\eta_p^2 = .27$, demonstrating that in both tasks, distractor-colour cue N2pcs differed reliably between the two experiments.

Discussion of Experiment 4

The results of Experiment 4 were clear-cut. As before, behavioural spatial cueing effects indicative of attentional capture were elicited only by target colour-cues and not by distractor-colour cues, regardless of whether participants searched for a single colour or two possible target colours. In marked contrast to Experiments 1 and 3, this behavioural evidence for task-set contingent attentional capture was now mirrored by a corresponding pattern of cue-elicited N2pc components. Only target-colour cues triggered reliable N2pc components, whereas distractor-colour cues did not. The fact that this was the case not only in the One Colour task but also in the Two Colour task provides strong support in favour of the claim by Irons et al. (2012) that attentional task sets can include multiple potential target colours simultaneously, and that these task sets are able to effectively control attentional selectivity during multiple-colour search. Direct comparisons of N2pc components to distractor-colour cues between experiments revealed reliable differences in the ability of these cues to attract attention between tasks where search displays contained two coloured items among four grey distractors (Experiment 3) and tasks where these displays included six differently coloured items (Experiment 4). This demonstrates that differences in the featural properties of visual search displays will have a strong effect on the search strategies that are employed by participants, and that this can determine whether or not formally task-irrelevant items can attract attention (see also Carmel & Lamy, in press, for interactions

between singleton-based and feature-based strategies during search for colour-defined targets). To study whether attentional task sets for multiple target features can control attentional selectivity effectively, it is essential to prevent participants from adopting a feature-unspecific singleton search mode. The results of Experiments 3 and 4 have shown that simply adding one additional task-irrelevant feature in the same dimension to each search display (as in Irons et al., 2012) may not be sufficient to achieve this aim, and that fully heterogeneous search displays may be required to guarantee that observers will adopt a feature search mode (see also Lamy, Leber, & Egeth, 2004, and Eimer et al., 2009, for studies for task-set contingent attentional capture with heterogeneous search displays).

General Discussion

The question whether top-down attentional control can be set simultaneously for different features remains controversial. Although there is some evidence that attentional task sets can represent only one feature in a given dimension at any one time (e.g., Wolfe et al., 1990; Dombrowe et al., 2011; see also also Olivers, Peters, Houtkamp, & Roelfsema, 2011), other findings suggest that visual selection can be guided more flexibly by multiple features (e.g., Adamo et al., 2008; Moore & Weissman, 2010; Irons et al., 2012). The current study was motivated by a recent demonstration of behavioural task-set contingent attentional capture effects during multiple-colour visual search (Irons et al., 2012). Colour cues that preceded search displays elicited spatial cueing effects indicative of attentional capture only when they matched one of two possible target colours but not when their colour was non-matching, even when target and distractor colours were not linearly separable in colour space. This suggests that multiple attentional control settings for different colours can be active simultaneously, and that task-set nonmatching objects can be effectively excluded from attentional processing. However, it remains unclear whether these behavioural cueing effects were generated during the initial rapid allocation of attention to task-set matching objects or at a later stage of attentional processing. To address this question, we used procedures that were closely modelled on the study by Irons et al. (2012), but also measured the N2pc component as an on-line electrophysiological marker of attentional capture by task-set matching and nonmatching colour cues.

In Experiment 1, the pattern of behavioural attentional capture effects confirmed the findings of Irons et al. (2012), with robust spatial cueing effects for colour singleton cues that matched one of the two target-defining colours, and no such effects for nonmatching colour cues. In contrast, reliable N2pc components were triggered not just by target-colour cues but also by distractor-colour cues, demonstrating that these cues could not be completely excluded from attentional processing. This dissociation between electrophysiological and behavioural correlates of attentional capture suggests that these effects are generated at different stages. Attention may initially be captured by distractor-colour cues but is then rapidly withdrawn from this location, resulting in the absence of spatial cueing effects in response to subsequent targets. Support for this two-stage account was provided in Experiment 2, which demonstrated reliable spatial cueing effects for distractor-colour cues when the SOA between cue and target displays was reduced to 100 ms. Experiment 3 showed that rapid attentional capture by distractor-colour cues, as reflected by reliable N2pc components to these cues, was not only elicited during search for two possible target colours (Two Colour task), but also in a One Colour task where participants searched for a single constant target colour. These observations suggest that the ability of distractor-colour cues to attract attention does not reflect an impairment of attentional selectivity that is specific to multiple-colour search, and may instead be a consequence of search being controlled at least in part by a feature-unspecific singleton search mode. This hypothesis was supported by the results of Experiment 4, where search displays contained six objects in six different colours, so that target detection had to be based on feature-specific attentional control settings for one or two target colour(s). Under these conditions, only target-colour cues triggered N2pc components, whereas no reliable N2pcs were observed in response to distractor-colour cues. This was the case not only in the One Colour task, but also in the Two Colour task, demonstrating that nonmatching colours can be selectively prevented from capturing attention during multiple-colour search.

Overall, the results of the current study show that when the demands of a particular search task require observers to adopt a strictly feature-specific task set, attentional target selection can be controlled by task settings that specify more than a single feature within a given dimension. During multiple-colour search, attention can be selectively allocated to objects that match one of the currently task-relevant colours, while objects with other

nonmatching colours can be ignored. The current N2pc results confirm and extend earlier behavioural evidence suggesting that attentional task sets can be set for multiple features simultaneously (e.g., Moore & Weissman, 2010; Beck et al., 2012; Irons et al., 2012). They are also in line with the results of a recent N2pc study from our lab (Grubert & Eimer, 2015) which showed that attention can be allocated rapidly and in parallel to two target objects even when these objects are defined by two different colours.

On the other hand, there is substantial behavioural evidence that attentional task sets for multiple features from the same dimension operate less efficiently than single-feature task sets (e.g., Wolfe et al., 1990; Meneer et al., 2009, Stroud et al., 2011; Dombrowe et al., 2011). Based on such observations, the Guided Search model assumes that the allocation of attention during visual search can be controlled by only a single feature from a particular dimension at any one time (Wolfe, 2007). The pattern of N2pc results observed in this study in response to target-colour cues are not in line with this proposal. If attentional guidance was always based on a top-down task set for a single target colour, N2pc components to target-colour cues should have been substantially smaller in the Two Colour tasks as compared to the One Colour tasks of Experiments 3 and 4, as only 50% of these cues would match the currently active colour task set in the Two Colour task. In fact, as can be seen in Figures 4 and 5, the target-colour cue N2pc components in the One and Two Colour tasks were very similar in size in both experiments, and comparisons of N2pc mean amplitudes confirmed that there were no significant differences (both $t(11) < 1.6$, $p > .152$). This suggests that the rapid allocation of focal attention to task-set matching objects, as reflected by the N2pc component to target-colour cues, is not impaired when task sets specify multiple instead of only a single feature from a given dimension. This conclusion is also supported by the fact the behavioural spatial cueing effects on trials with target-colour cues did not differ in size between the One and Two Colour tasks in Experiments 3 and 4.

The pattern of behavioural spatial cueing effects and N2pc components observed in the Two Colour tasks of the present study is remarkably similar to the results described in the spatial cueing literature for tasks where participants searched for a single target-defining feature (e.g., colour, onset, apparent motion). Such studies have consistently shown that attentional capture by salient visual objects (singleton cues) is contingent on whether such objects match pre-defined target properties as represented in a current task set. Faster RTs

to targets at cued relative to uncued locations and solid N2pc components were found in response to task-set matching cues, but not for cues that did not match the target dimension during singleton search (Eimer & Kiss, 2008; Eimer & Kiss, 2010; Folk & Remington, 1998; Folk et al., 1992; Folk, Remington, & Wright, 1994) or the target feature during feature search (Eimer et al., 2009; Lamy & Egeth, 2003; Lamy, Leber, & Egeth, 2004; Lien et al., 2008). The present study has shown that these behavioural and electrophysiological markers of task-set contingent attentional capture are virtually identical when task sets contain one or two possible target colours, which strongly suggests that attentional guidance processes can operate equally efficiently during single-feature and multiple-feature search.

It is important to note that in the present experiments and in all previous studies that employed spatial cueing procedures to demonstrate the task-set contingent nature of attentional capture, including investigations of attentional task sets during single-colour or multiple-colour search (Irons et al., 2012), target-defining features remained constant within experimental blocks. This may have consequences for the way in which information about these features was represented during task performance. Recent behavioural and ERP studies have suggested that when participants search for the same target object across a number of trials, representations of target-defining features are no longer held in working memory, but are transferred to long-term memory (e.g., Carlisle, Arita, Pardo, & Woodman, 2011; Gunseli, Olivers, & Meeter, 2015). The question whether attentional task settings for multiple colours are represented in working memory or long-term memory is important from a theoretical perspective, as working memory capacity can typically hold up to three or four items (e.g., Vogel, Woodman, & Luck, 2001). Top-down attentional templates that are activated during visual search are assumed to be held in visual working memory, and the capacity of such templates may even be more limited than the overall capacity of working memory (e.g., Olivers et al., 2011). In fact, the most severe limitations in the capacity of top-down attentional task sets during visual search have been demonstrated in studies where observers have to activate new search templates on every trial, which implies that these templates are held in working memory. For example, Houtkamp and Roelfsema (2009) demonstrated massive impairments of target detection performance in rapid serial visual presentation (RSVP) tasks when observers search for two possible objects relative to single-object search. Modelling of these results suggested that exactly one attentional template

can be active at a time (see Olivers et al., 2011, for further discussion). Such severe limitations in the capacity of top-down task settings may be specific to situations where these settings are held in working memory. When target-defining attributes remain constant, as in the present study, they could in principle be represented in long-term memory, where no such capacity limitations apply. If this is correct, the finding that top-down task settings can specify multiple constant target colours simultaneously is not necessarily at odds with the suggestion that only a single search template can be maintained in working memory at any given time. To investigate this possibility, future spatial cueing studies of task-set contingent attentional capture could employ varied mapping designs where target-defining colours change across successive trials. Under such conditions, search templates for single or multiple target colours have to be activated anew for each individual trial, and will therefore be represented in visual working memory. If working memory can hold only one colour template at a time, attentional selectivity should be strongly impaired in such varied-mapping tasks when targets can have different colours. As a result, behavioural and electrophysiological markers of task-set contingent attentional capture should reveal qualitative differences between single-feature and multiple-feature search.

The observation that distractor-colour cues remained able to capture attention during both single-colour and two-colour search in Experiment 3 where target displays contained two coloured items among four grey objects, but not in Experiment 4 where these displays included six items in six different colours underlines the important impact that differences in the visual attributes of search displays may have on attentional selection strategies adopted by observers. Attentional capture by items in a task-irrelevant colour implies that this colour was represented in a currently active task set, which would be the case if attention was at least partially guided by a feature-unselective colour singleton search mode (see above). Alternatively, it is possible that participants chose to attend not only to target colours, but also to the distractor colour when all search displays included an item in the same task-irrelevant colour together with the target and four grey items. For example, briefly attending to the known distractor colour might have aided the subsequent selection of the other coloured object in the display. Such a strategy would result in attentional capture by distractor-colour cues, because these cues always matched the constant distractor colour in the search displays (as in the original study by Irons et al.,

2012). If this was the case, nontarget-colour singleton cues should no longer capture attention, as reflected by reliable N2pc components, when their colour differs from that of the subsequent distractor item. This possibility could be assessed in future N2pc studies of multiple-colour search.

In summary, the current study has provided new electrophysiological support for the hypothesis that attentional control processes can be set flexibly and selectively for a set of specific features within a given dimension. The allocation of attention can be guided effectively by attentional task settings for multiple target colours, resulting in the spatial selection of objects that match the currently active task set and the exclusion of nonmatching objects from attentional processing.

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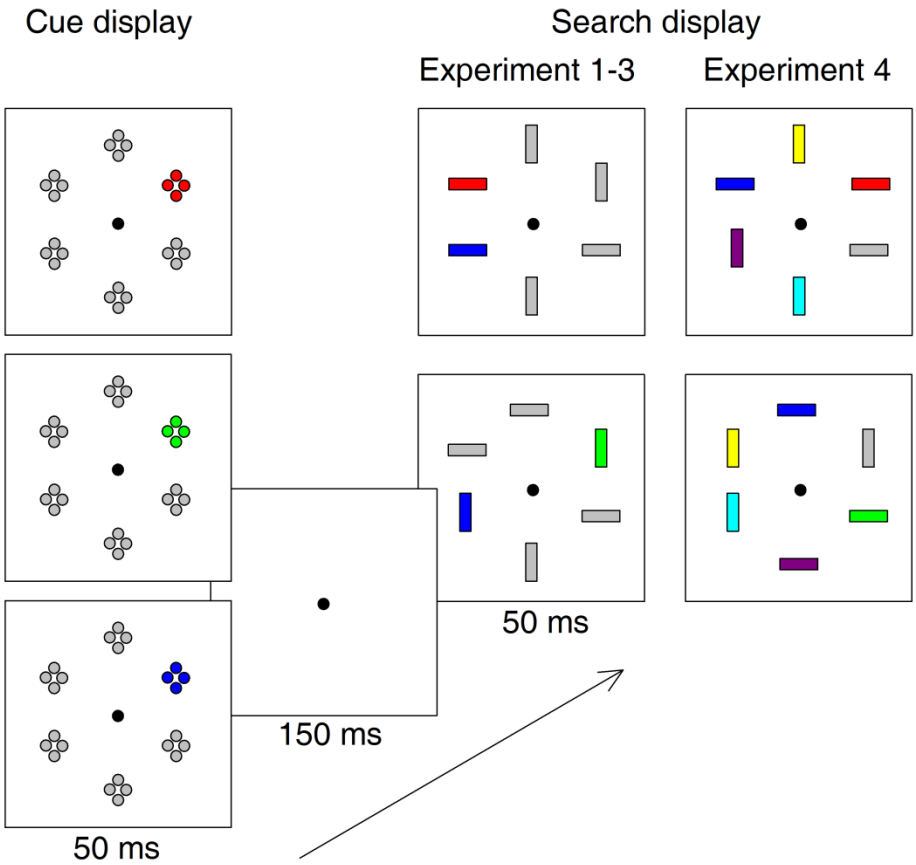

Figure 1. Schematic illustration of the cue and search displays used in the Two Colour tasks of Experiments 1 to 4. The background was originally black. Cue displays contained either a target-colour (e.g., red or green) or a distractor-colour item (e.g., blue) among five grey items. Search displays contained one bar in one of the two possible target colours (e.g., red or green), one distractor-colour bar (e.g., blue), and four grey bars (Experiment 1 to 3). In Experiment 4, search displays contained six bars in six different colours, including the target and distractor colours. In the One Colour tasks of Experiments 3 and 4, participants searched for a single constant target colour, and there were only two possible cue displays (containing either a target-colour or a distractor-colour singleton). Cue and search arrays were both presented for 50 ms, and were separated by an inter-stimulus interval of 150 ms. In Experiment 2, a shorter inter-stimulus interval of 50 ms was used. A coloured copy of Figure 1 is available in the online version of this article only.

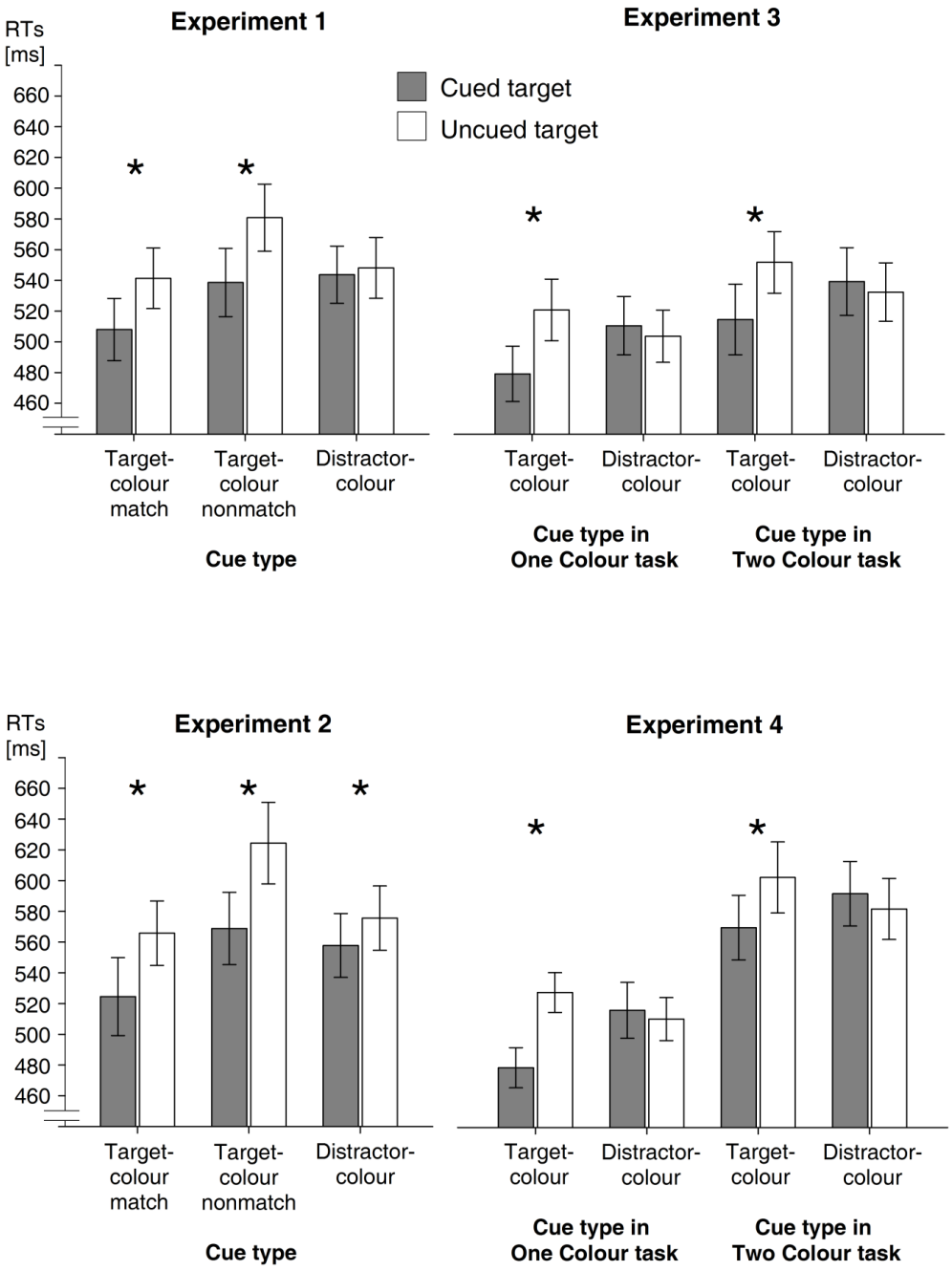

Figure 2. Mean correct response times (RTs, in milliseconds) to targets at cued and uncued locations in Experiments 1 to 4. For Experiments 1 and 2, results are shown separately for trials with target-colour cues that matched or did not match the colour of the subsequent target bar, and trials with distractor-colour cues. For Experiments 3 and 4, results are shown for trials with target-colour and distractor-colour cues, separately for the One Colour and Two Colour tasks. Error bars reflect mean standard errors. Asterisks reflect significant cueing effects (faster RTs at cued relative to uncued target positions).

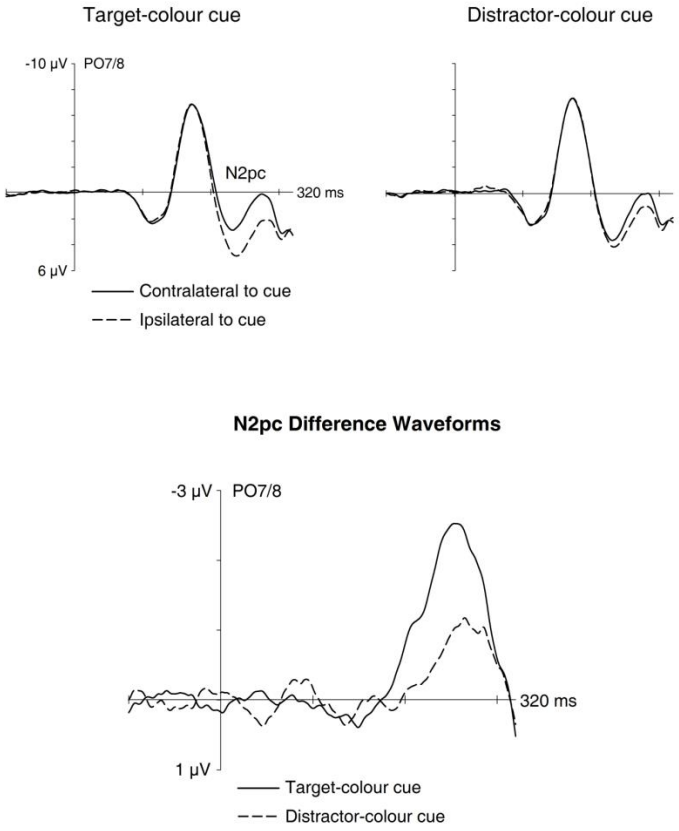

Figure 3. Grand-average event-related potentials (ERPs, in microvolt) measured in Experiment 1 at electrode sites PO7 and PO8 contra- and ipsilateral to the location of target-colour and distractor-colour cues (top panel). The bottom panel shows difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for target-colour and distractor-colour cues. Ticks on x-axes represent 100 ms intervals.

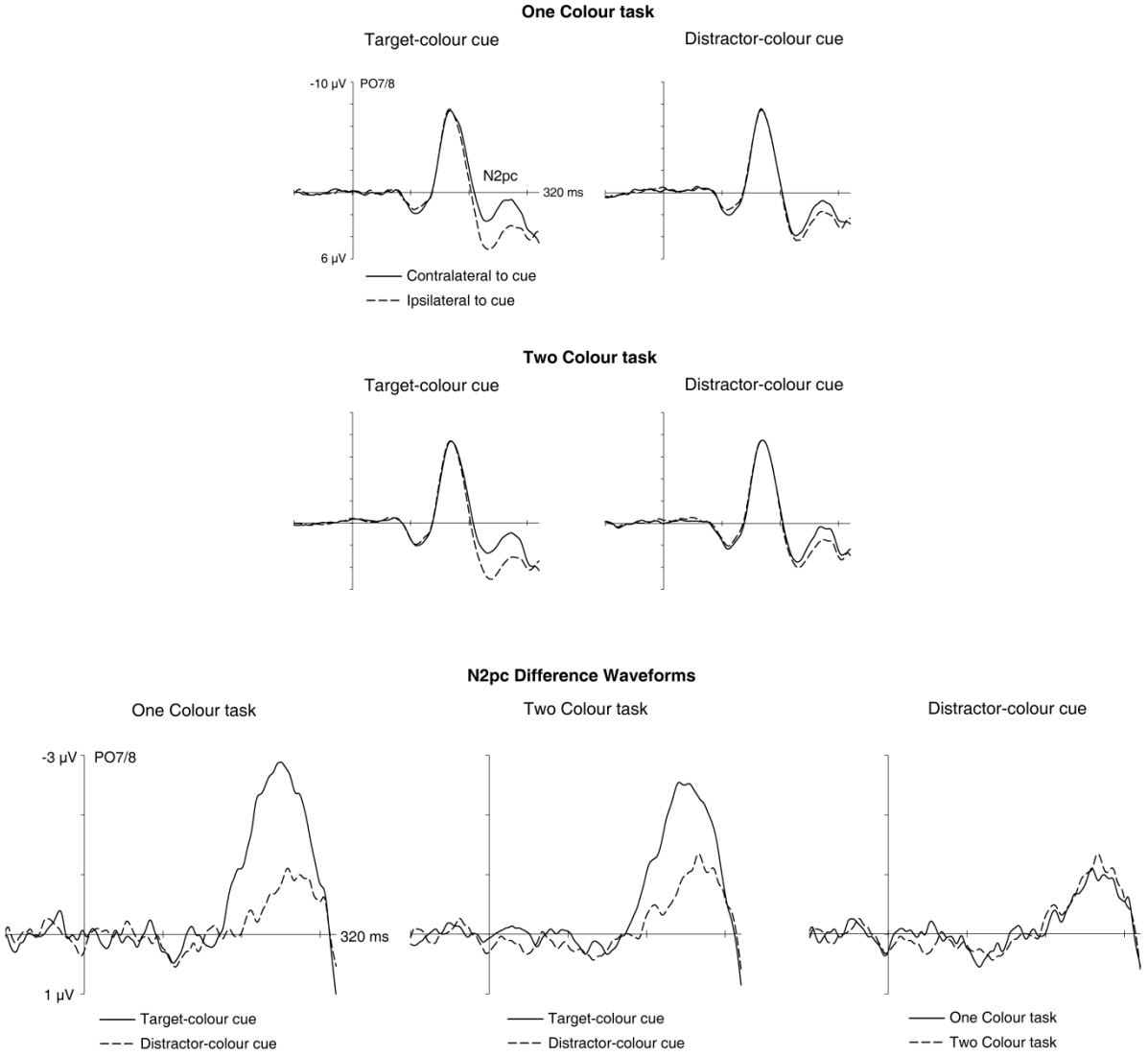

Figure 4. Grand-average ERPs measured in Experiment 3 at electrode sites PO7 and PO8 contra- and ipsilateral to the location of target-colour and distractor-colour cues. ERPs are shown separately for the One Colour task (top panel) and the Two Colour task (middle panel). The bottom panel shows contralateral-ipsilateral N2pc difference waveforms for target-colour and distractor-colour cues in the One Colour task (left) and the Two Colour task (middle), as well as a direct comparison of N2pc components to distractor-colour cues between the One Colour and Two Colour tasks (right). Ticks on x-axes represent 100 ms intervals.

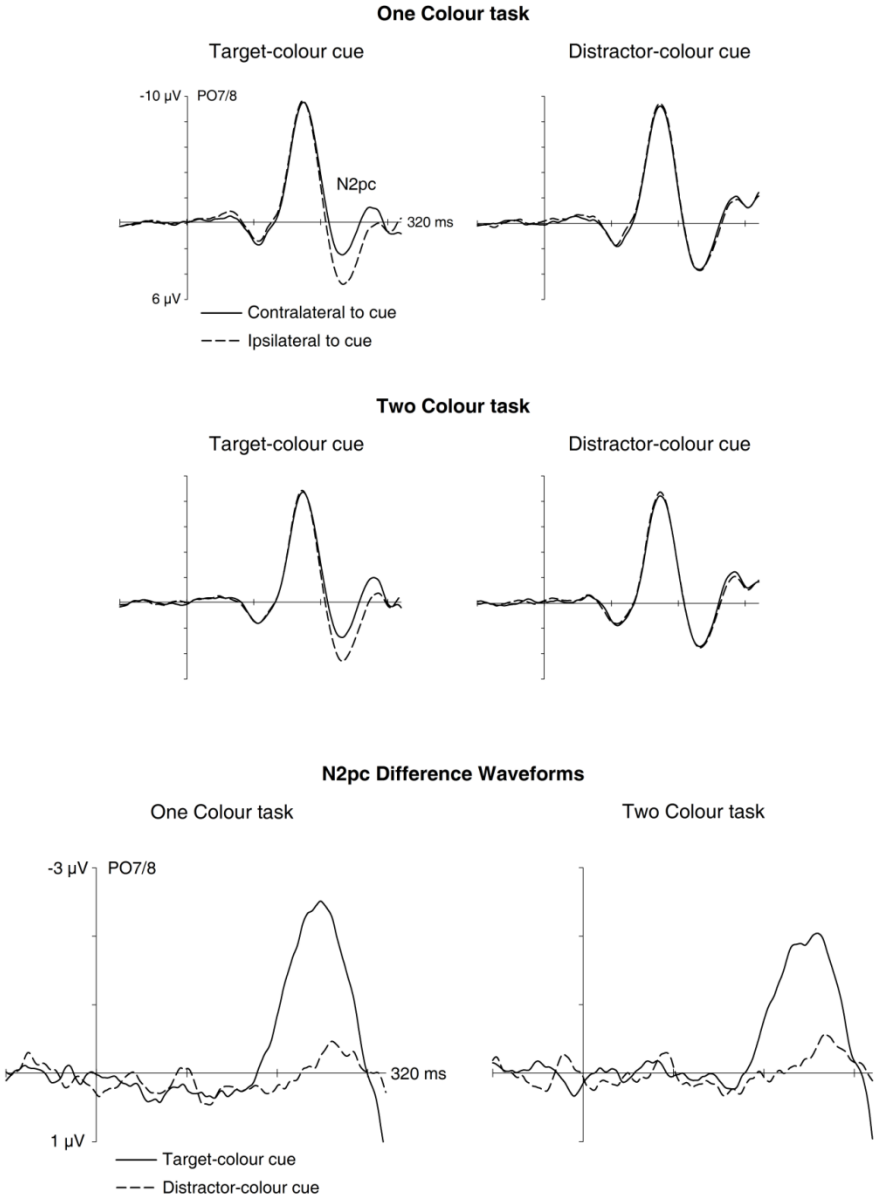

Figure 5. Grand-average ERPs, measured in Experiment 4 at electrode sites PO7 and PO8, contra- and ipsilateral to the location of target-colour and distractor-colour cues, in the One Colour and Two Colour tasks (top and middle panel). The bottom panel shows contralateral-ipsilateral N2pc difference waveforms for target-colour and distractor-colour cues in the One Colour and Two Colour tasks. Ticks on x-axes represent 100 ms intervals.